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SUPERCONDUCTING GENERATORS FOR AIRBORNE APPLICATIONS AND YBCO-COATED CONDUCTORS (PREPRINT)

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**Power Generation Branch
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14. ABSTRACT With the development of high-power applications, especially those on air platforms, power generation systems above the megawatt level will be required. Superconducting generators can address this need. Recently, several successful rotating machinery projects demonstrated the practicality and feasibility of the technology using the high temperature superconducting BSCCO wire. With progress of the newer superconducting YBCO-coated conductor to longer lengths, addition improvement can be made to these superconducting devices. This presentation will address the use of the superconducting generator from an airborne perspective and then address the benefits and some issues for the employment of YBCO coated conductors in future demonstrations.					
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Superconducting Generators for Airborne Applications and YBCO Coated Conductors

Paul N. Barnes, George A. Levin, and Edward B. Durkin

Abstract—With the development of high-power applications, especially those on air platforms, power generation systems above the megawatt level will be required. Superconducting generators can address this need. Recently, several successful rotating machinery projects demonstrated the practicality and feasibility of the technology using the high temperature superconducting BSCCO wire. With progress of the newer superconducting YBCO coated conductor to longer lengths, addition improvement can be made to these superconducting devices. This presentation will address the use of the superconducting generator from an airborne perspective and then address the benefits and some issues for the employment of YBCO coated conductors in future demonstrations.

Index Terms—high-temperature superconductors, YBCO, superconducting tapes, superconducting wire, superconducting rotating machines, superconducting materials, YBCO coated conductors.

I. INTRODUCTION

A prominent need of future airborne power systems of megawatt-class output is minimizing the size and weight of the power generation and ancillary support systems. One approach for achieving higher power density within the generator is to maximize the magnetic flux density, which can be enabled by superconductors with very high-field ampere-turns [1], [2]. The newer high temperature superconducting (HTS) wire typically takes the form of a thin flat tape as opposed to a round wire.

The central challenge is to effectively integrate the superconducting coil and its cryo-cooling subsystem. This issue is magnified when pursuing the higher rotating speeds also conducive to increased power density, if the conductor and cooling system are rotor-mounted. The added challenge of a power generation system that increases its power density is the increased per-unit mass heat generation for a given level of losses, requiring closely-integrated and efficient integrated thermal management.

Most power machinery demonstrations to date have used

the bismuth strontium calcium copper oxide (BSCCO) superconductor, being the first HTS conductor to be scaled up. However, a newer yttrium barium copper oxide (YBCO) superconductor has been developed that has in the past year been scaled to lengths that it can now be used in power application demonstrations. YBCO has several significant advantages over the BSCCO wire: in-field operation at liquid nitrogen temperatures while maintaining high critical currents in magnetic fields up to several Tesla, the ability to reduce ac losses in the architecture, improved strain tolerance, and lower production costs. Scale-up of the YBCO coated conductors at manufacturers has improved the quality and length of wire available—from 10^5 A/cm², self-field, at several centimeters length a few years ago to lengths of 600 m and longer with 10^6 A/cm² performance [3-4].

II. MULTIMEGAWATT ELECTRIC POWER SYSTEM

A recent effort by the U.S. Air Force has been to advance the power technologies in support of high-power applications (HPA) being placed on airborne platforms. Specifically, with the large onboard electrical power demands, it is necessary to develop the required power generation, distribution, and conditioning technologies required for the airborne use of these applications. One program is the megawatt-level electric power system (MEPS). The Broad Agency Announcement for the program stated the specific objective of the MEPS program was the development and testing of the superconducting power system for airborne HPA.

In 2004, the Air Force Research Laboratory (AFRL) contracted with General Electric (GE) to design, build, and test a MEPS configuration including a superconducting generator, cooling systems, and power conditioning system. The cornerstone of the program was a high-temperature superconducting (HTS) generator which would demonstrate technologies leading to later HTS machine designs with specific power ratios exceeding 4.0 kW/lb (8.82 kW/kg). The machine configuration chosen by GE for design was a homopolar inductor alternator (HIA) which locates the superconductor coil within the stator, thereby eliminating rotational loads on the coil while also simplifying the rotor design to a more rugged structure. Removing the HTS coil from the rotor also allows higher rotating speeds that can again also improve overall power density.

GE completed its build of a 1-megawatt class HTS generator in early 2007 and the following tests provided the

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first successful full-power run of an HTS machine for the USAF. The generator produced 1.3 MW output at its design speed of 10 krpm, and achieved 97% overall efficiency even accounting for cryo-cooler losses. This generator demonstration not only validates the HIA concept, but also advances multiple technologies that can support future HTS machine designs utilizing the latest-generation superconductors such as YBCO. GE is also performing the conceptual design of a 5-MW HIA baselined to meet the above-noted specific power ratio goal.

III. YBCO COATED CONDUCTORS

As mentioned, the YBCO coated conductors offer many advantages over the previously used BSCCO tape. This point is underscored by the fact that many companies are switching to the production of YBCO tapes from the BSCCO tapes as they scale-up the processing of the YBCO conductor. In the U.S. the production of BSCCO has been completely halted with sales limited to existing stocks. The newer YBCO conductor provides “form, fit, and function” replacement to have a minimal impact on application usage. Table I provides a comparison of the two conductors.

Because YBCO coated conductors are now made reel-to-reel in hundreds of meter length, research and development needs to shift toward improving the conductor and applying the conductor to the variety of applications it has, in this case, the generator. This does not mean that additional improvements to the basic conductor architecture are not necessary or possible. In the discussion that follows improving the critical current and minimizing ac loss are briefly discussed.

TABLE I
BSCCO WIRE AND YBCO WIRE COMPARISON.

Property	BSCCO (now) ^a	YBCO (now) ^a	YBCO (near term) ^b
Cost (relative)	16-20	50-100	3-5
Operating Temp. (in-field)	22 - 35 K	45 - 55 K	60 - 70 K
J_E - Eng. Current Density ⁱ 77 K, self-field	7 - 17 kA/cm ²	8 - 29 kA/cm ²	15 - 50 kA/cm ²
J_E - Eng. Current Density 65 K, 2.5T/c	negligible	2.5 - 8 kA/cm ²	8 - 20 kA/cm ²
Tensile Strain 77K	0.10 - 0.40%	0.30 - 0.45%	0.30 - 0.60%
Length	Up to 1.5 km	Up to 600 m	1 - 1.5 km

^bBased on manufacturer's data sheets. BSCCO data composite from American Superconductor Corp. and Sumitomo Electric, Inc.; YBCO data composite from American Superconductor Corp. and SuperPower, Inc.

ⁱProjection based on trends.

^dRelative based on some reported \$/kA-m, 77K SF, figure of merit data.

A. Higher Currents

An important parameter for enabling superconducting generator operation at higher temperatures or to provide a more compact winding is increasing the amount of current the HTS tape can carry. This can be done by improving the in-field performance of the critical current density (J_c) in the superconductor. It can also be done by improving the overall critical current density of the wire (J_E) since the superconducting layer is only a fraction of the composite wire's architecture. However, the metallic foil that serves as the substrate has been reduced to 50 - 80 μm already and a greater focus should be on increasing the critical current of the superconducting layer in the coated conductor architecture [5] - [7]. Minimum mechanical strength of the substrate will also be necessary and prevents making the substrate arbitrarily thin.

Improvement in the J_c of the superconducting layer itself can be done by incorporating magnetic flux pinning centers. Nanoparticles have been demonstrated as the best pinning centers to date and can be incorporated by a variety of methods [5], [8] - [14], being first demonstrated by Haugan et al. Recently, nanoparticulate pinning has provided over two orders of improvement to the J_c of YBCO at several tesla using a BaSnO_3 (BSO) nanoparticle [13], [14]. There is some initial success in transitioning the nanoparticle approach to industrial methods [15], but the full value of improvement in industry is yet to occur and deserves a focused effort to fully transition the technology to industrial processing methods.

A potential avenue to incorporate these pinning centers by a variety of processing methods is the addition of minute amounts of deleterious elements. Minute doping in this manner ($\leq 1\%$ of Y substitution by a deleterious rare earth) into high quality YBCO thin films has been demonstrated to provide improvement of the film's in-field J_c [12]. It was accomplished without additional optimization of the deposition parameters in [12]. Interestingly, instead of typical site substitution for Y, the deleterious rare earths seem to form nanoparticulates, explaining why the enhanced performance over standard rare earth substitutions by the preferred elements.

B. Lower AC Losses

There are several channels of energy dissipation in a rotating machine, such as a generator. Specific to the superconducting winding are eddy-currents in the stabilizer and substrate, weak ferromagnetic losses in Ni-W substrate, but the most detrimental is the loss in the superconducting layer (hysteresis loss) [22-28]. This is especially true for high speed generators, since the losses increase with increasing frequency.

In the field windings ac asynchronous feed back is possible. Shielding must be added to protect the conductor from ac losses. This issue was pointed out in a Westinghouse

project funded by the U.S. Air Force. In this contract Westinghouse built a 5 MVA, 400 Hz machine where the electromagnetic shield on the rotor was considered a major problem of the superconducting machine. Excessive heating in the shield resulted from the load-induced varying fields [23]. A more ac-tolerant YBCO conductor may potentially eliminate the shielding requirement, but will at least lower the amount of necessary shielding.

A way to reduce the hysteresis loss in the YBCO coated conductors is by dividing them into a large number of parallel filaments separated by narrow resistive barriers. This was originally proposed by Carr and later documented in [24]. The physical mechanism of loss reduction as the result of subdivision of a uniform superconducting film into many filaments is similar to that in normal multifilament conductors (such as Litz wire). The total hysteresis loss in the conductor comprised of many superconducting stripes is reduced in proportion of the width of an individual stripe. An experiment on small samples of YBCO films deposited on LaAlO₃ substrate has confirmed the validity of that suggestion [25].

Measurements of the magnetization losses in actual multifilamentary YBCO coated superconductors have also been reported recently [26-33]. In Refs.[26] and [28] two 10 cm long samples of YBCO-coated conductor, one control and the other striated, were subjected to a magnetic field normal to the wide face of the tape and varying at different linear frequencies in the range 11-170 Hz with a magnetic induction amplitude up to 70 mT. The total loss in the multifilament conductor was reduced by about 90% in comparison with the uniform conductor at full field penetration at a sweep rate B_f as high as 3T/s [28]. Similar results were obtained on RABiTS conductors [29].

It should be noticed that all above mentioned experiments have been carried out on coated conductors without copper stabilization. Only a thin (a few microns thick) silver layer was covering the YBCO film. Truly stabilized multifilament coated conductor will require the copper stabilizer to be striated in the same pattern as the underlying superconducting film.

SuperPower, Inc. has taken efforts recently to scale up the filamentary concept to reel-to-reel processing using lithography techniques [5]. The system used provides narrow grooving to minimize the amount of superconductor removed. Slitting to smaller widths than the standard 4 mm tapes has also been demonstrated. They have also been able to twist the YBCO coated conductor while maintaining at least 95% of the original critical current.

IV. CONCLUSION

The newly available YBCO coated conductors offer many advantages over the BSCCO tape previous used in motor and generator demonstrations. The benefits of compact high-power superconducting machinery, such as the MEPS generator demonstrated by GE, can be enhanced by use of the

YBCO wire. A comparison of the properties of the YBCO vs. BSCCO shows that it not only is superior in several functional aspects, but will also cost less. Even so, there is additional development that the YBCO wire can use to fully exploit its capability in machines.

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superconducting generators with 1-5 megawatt output and associated power systems.

VI. BIOGRAPHIES



Paul N. Barnes is a principal research physicist and the Research Group Leader for the Power Generation Branch of the Air Force Research Laboratory (AFRL). The group includes high temperature superconductivity (HTS), magnetic materials, carbon nanotubes, and dielectric insulation research. His research group also oversees several contractual development programs. Dr. Barnes received his PhD in Physics from the University of Illinois at Urbana-Champaign. He has authored or co-authored over 100 papers. His superconductivity group has been awarded Star Team Status by the Office of Scientific Research and he has received the Heron Award, named Scientist of the Year and named as an AFRL Fellow. He also serves on several boards and committees for superconductors and cryogenic materials.



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